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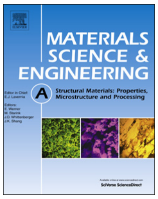

Creep-fatigue crack growth behavior of G115 steel at 650 °C

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ABSTRACT

The micro-mechanism of creep-fatigue interaction of novel 9% chromium tempered martensitic steel, G115, was investigated after creep-fatigue crack growth experiment using compact tension (CT) specimens. It indicated that the mode of crack growth changed from transgranular to intergranular when the crack growth stage changed from the initial to the accelerated region. At the initial crack growth region, fatigue striations and fatigue bands were observed. Then, creep voids were nucleated and the number increased. In addition, many secondary cracks were generated at the second stage and the number of cracks were increased steeply when the crack growth rate was accelerated at the tertiary crack growth stage. Furthermore, the variation of the creep, fatigue and the interaction damage during the crack growth process was analyzed using numerical simulation. The results agreed with experiment which illustrated that creep damage increased and fatigue damage reduced from the initial to the third crack growth stage and the increased interaction damage aggravated the crack propagation.

1. Introduction

Continuous exhaustion of fossil resources and the effects of environmental pollution worldwide make an urgency for power plants. As for them, the improvement the thermal efficiency is an important way to solve this problem. Thus, the thermal power units are facing the trend of developing forward high temperature and high pressure, and the temperature rises from 600 °C to 650 °C. But the higher temperature used, the higher requirement for the material needed.

Therefore, it is an urgent task to produce steels that can operate at higher temperatures and pressures [1–6]. The 9–12% chromium martensitic heat resistant steels had good creep properties and had been widely used in USC coal-fired power plants [7–11]. However, these traditional martensitic steels, such as P91, P92 [12–14] and P122 [15–17] would lose their strength significantly when the service temperature was higher than 650 °C [18]. This was due to the recrystallization and the precipitation coarsening and dissolution at high temperature. To solve this problem, people began to develop new kinds of martensitic heat-resistant steel with higher creep properties and steam resistance at higher temperature. 9Cr–3W–3Co steels, which were first developed by the National Institute of Materials Science in Japan, are expected to be used at 650 °C and had been studied extensively such as alloy design [19,20], the microstructure evolution [21,22], creep behavior at high temperature [23–25], etc. China Steel Research Institute developed a new kind of tempered martensitic heat-resistant steel, G115, which exhibited excellent creep properties at 650 °C. It can be served as the candidate material for USC power plants at 650 °C. The heat treatment on the strength [27,28], microstructure evolution and fracture mechanism during short-term creep [26], the tensile properties and the constitutive equation at high temperature [30] and various other [29] had been studied.

However, for the components made from G115 steel, in addition to the effect of high temperature, the cyclic load was also a great challenge for the performance. The cyclic load in high temperature and pressure made the working parts operate in the creep-fatigue interaction state. With the increase of cycle number, micro cracks occurred in components and gradually increased, eventually led to the failure of components. Jianfeng Wen et al. [31] has researched creep crack growth under monotonic and cyclic loading by grain boundary cavitation. Ashok Saxena [32] studied the importance of creep and creep–fatigue considerations on components operating in harsh, high temperature environments. Hongyang Jing et al. [33] researched creep-fatigue crack growth behavior for P91 steel at 625 °C considering creep-fatigue interaction through finite element simulation approach.

But the researches on the performance and mechanism of G115 steel in this state were very few. Kexian Shi et al. [34] showed that the fatigue action may reduce the initiation time of creep-fatigue cracks and accelerate the crack growth rate. Lianyong Xu et al. [35] characterized crack growth behavior and damage evolution in P92 steel under creep-fatigue interaction conditions, combining with a non-linear creep-fatigue interaction damage constitutive model. It illustrated that the time dependent crack growth rate increased as the duration period was

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reduced. Vani Shankar et al. [36] studied the time dependent effects on the low cycle fatigue (LCF) behavior of 316 L(N) stainless steel weld joint and found that the dynamic strain aging manifested in the form of negative strain rate sensitivity and played a significant role in fatigue life reduction at 823 K and creep effects were dominant at 873 K and the weld joint exhibited tensile dwell sensitivity.

The difference of mechanism in the stable crack growth stage were studied. J.P. Tan et al. [37] investigated the effect and mechanism of out-of-plane constraint on creep crack growth rates with scanning electron microscope (SEM). It showed that the effects was related to C*-integral levels, increasing the crack growth rate when it was low and no or little effects when it was high. N. Ab Razak et al. [38] used scanning electron microscope (SEM) analysis to confirm the influence of frequency on the mode of cracking. Guodong Zhang et al. [39] obtained the time dependent failure assessment diagram (TDFAD) by using modified R6 Option2 with observation of micro fracture feature of specimens. D.G. Leo Prakash et al. [40] elucidated some microscopic aspects of crack growth and established a connection with microscopic conditions and parameters of crack growth.

Nevertheless, there were few studies about the observation and detailed analysis of the mechanism of different crack growth stages. Therefore, in this paper, the creep-fatigue crack growth behavior of G115 steel at different stages was observed and analyzed in detail to study the change of damage mechanism by scanning electron microscope (SEM). Moreover, the creep damage and fatigue damage in each stage were further studied by finite element simulation. The microscopic mechanism of creep-fatigue crack growth of G115 was studied by the approach of combining experiment and simulation.

2. Experimental procedures

2.1. Materials

In this study, a novel 9% chromium tempered martensitic steel, G115, was selected to be tested. The original material was extracted from a pipe, with an outer diameter of 60.0 mm and a thickness of 10.0 mm. The pipe was heat-treated by normalized at 1100 °C for 1 h and then tempered at 760 °C for 3 h. Its chemical composition is given in Table 1.

2.2. Specimen

CT specimens have been widely employed in Creep-fatigue crack growth tests under external cyclic loading with holding time to realize the interaction between creep and fatigue. In this paper, CT specimen with a thickness of 7.5 mm was used and holding time was 60 s. Details of the geometry and dimension of the CT specimen are shown in Fig. 1.

2.3. Creep-fatigue crack growth test

After the CT specimen was machined, wire-electrode cutting was used to generate a gap to make the pre-crack easily to be machined ahead of the notch of specimen. The pre-crack was 3.0 mm which was machined by wire-electrode cutting a depth of 0.5 mm with 0.12 mm diameter wire into the notch root, and then generated a crack of 2.5 mm by fatigue load cycling at room temperature. The max value of load was less than that used in crack growth test.

On the basis of ASME E2760-10 code [41], CT specimen was tested at 650 °C using electronic tensile creep test machine. The temperatures were kept within ± 1 °C during test. The experimental conditions are shown in Table 2. The creep-fatigue crack growth length was measured by an electrical potential drop method. An electric current was applied to the specimen and then the value of an electric potential drop was measured. The crack growth length was usually calculated using Johnson's equation for CT specimen [42,43], as shown in the following equation:

$$a = \frac{2W}{\pi}\cos^{-1}\left\{\frac{\cosh(\pi Y_0/2W)}{\cosh\left[(V/V_0)\cosh^{-1}(\cosh(\pi Y_0/2W)/\cos(\pi a_0/2W))\right]}\right\}, \tag{1}$$

After the creep-fatigue crack growth test, the failed specimen was fractured and then to be analyzed by scanning electron microscope (SEM) to study the micro-mechanism of creep-fatigue interaction.

Table 1
Chemical composition (wt%) of the as-received G115 steel.

Element	C	Cr	W	Co	Cu	Mn	Si	V	Nb	N	B	Fe
Amount	0.08	8.8	2.8	3.0	1.0	0.5	0.3	0.2	0.06	0.008	0.014	Bal.

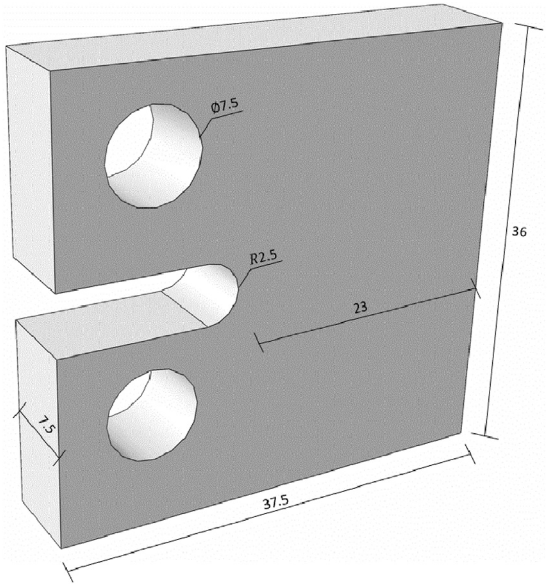

Fig. 1. Details of the geometry and dimension of the CT specimen.

Table 2
Experimental conditions of creep-fatigue crack growth tests.

a_0 (mm)	W (mm)	B (mm)	K (Mpa $m^{1/2}$)	P (N)
13.04	30.06	7.52	18	4242

3. Finite element method analysis

3.1. FEM model

In order to study the mechanism of creep-fatigue crack growth of G115, and to research the change of creep damage and fatigue damage and the interaction between the two factors during the crack growth process, the method of finite element analysis was used though the commercial software ABAQUS.

The FEM model was shown in Fig. 2. As it was shown, considering the geometrical symmetry of CT specimens, a quarter 2D model of CT specimen with plane strain mesh was established, dimensions and sizes of which were the same to the tested specimens. The mechanical properties of G115 steel at room temperature and at 650 °C employed in the present study were shown in Table 3. They were used for the subsequent thermal exposure and creep-fatigue analyses. Because of the symmetry plane along the ligament in the CT specimen, a symmetry constraint in Y direction was added. The model used first order (linear) 4-node bilinear plane strain quadrilateral elements with reduced integration and hourglass control (ABAQUS CPE4R). To eliminate mesh